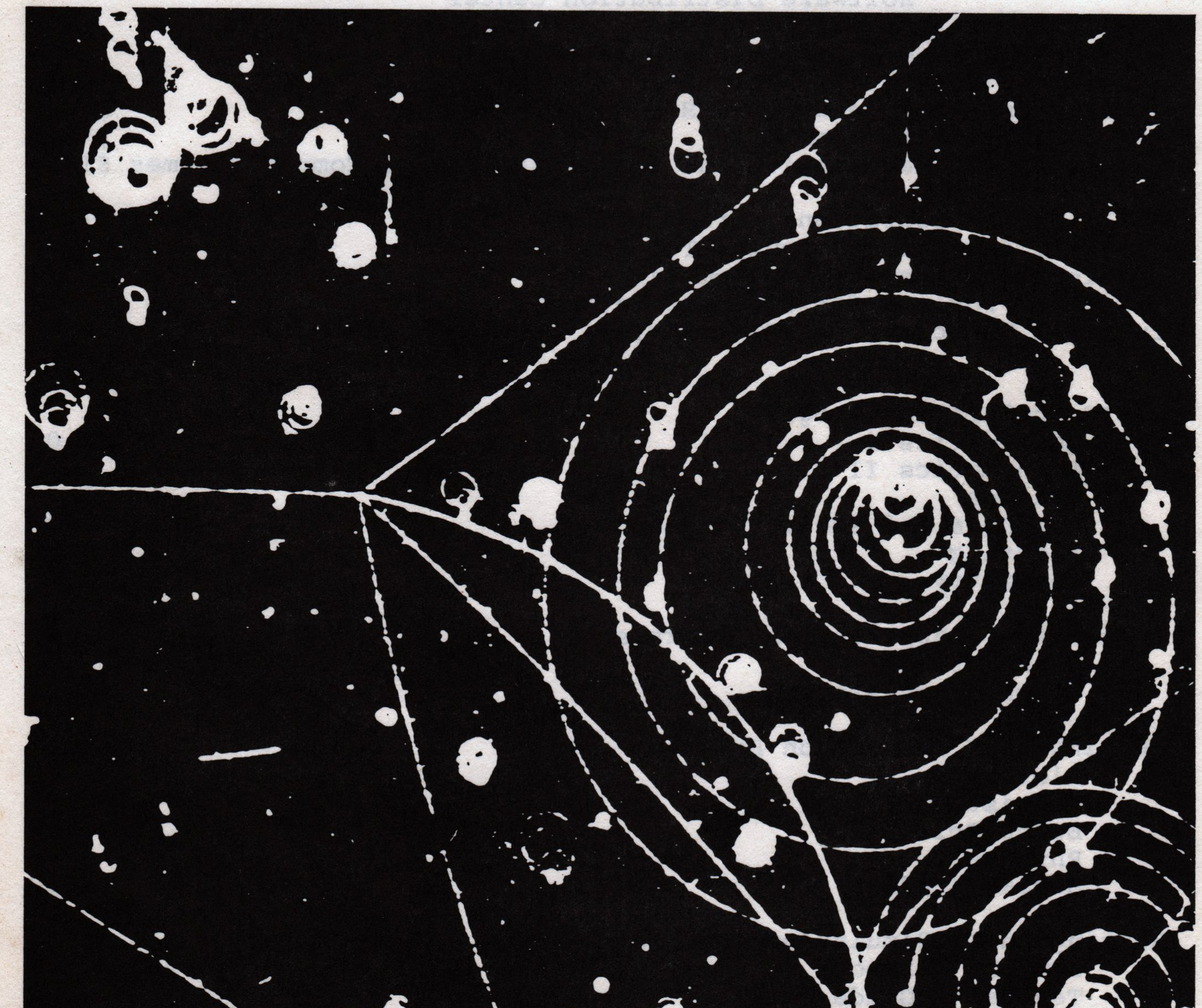
DIGITAL EQUIPMENT CORPORATION

TEACHER'S GUIDE $ .50

# education

# Huntington II Simulation Program – SCATR



digital

# DIGITAL EQUIPMENT CORPORATION
# EDUCATIONAL PUBLICATIONS

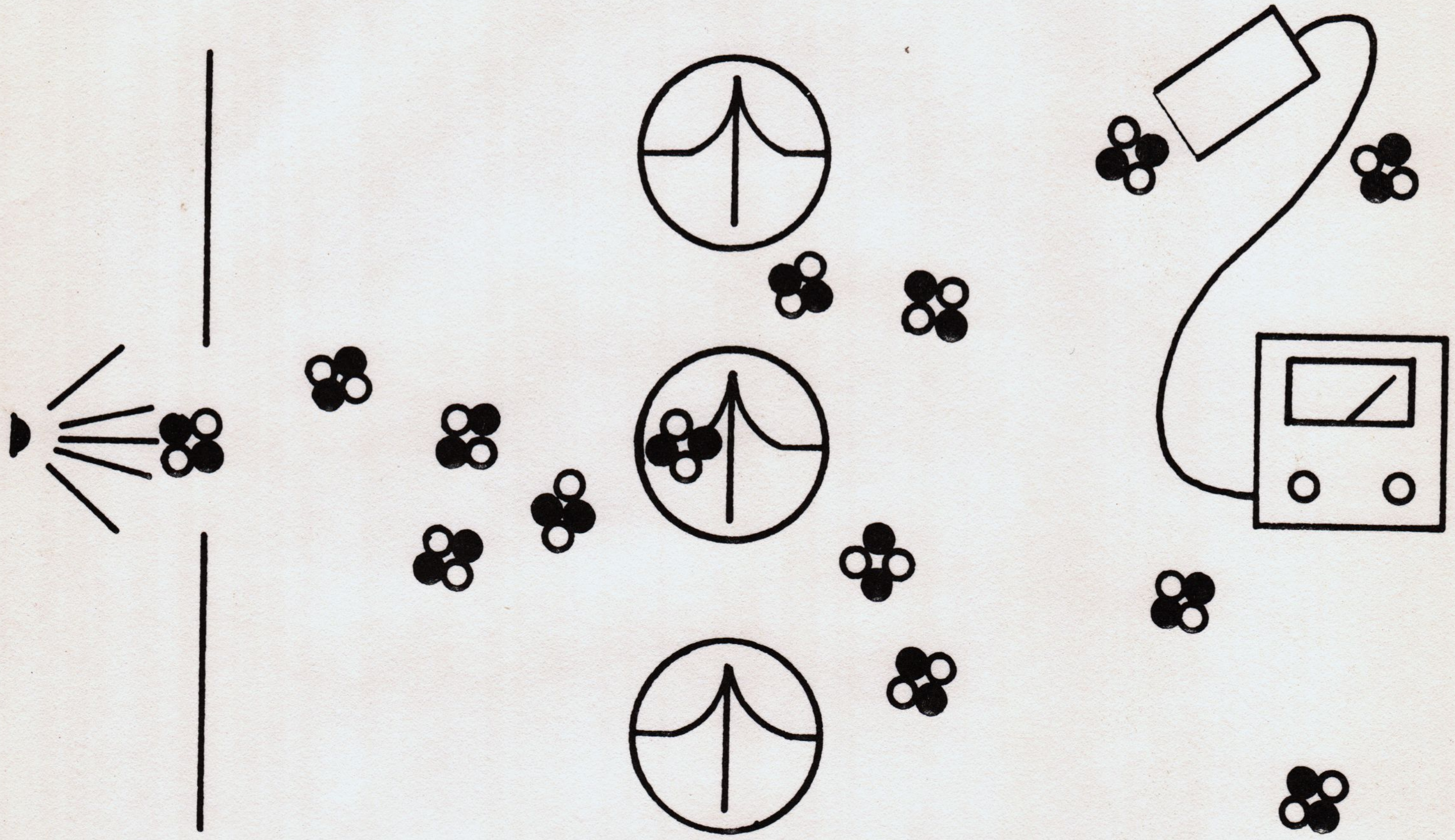
A partial list of the publications in the continuing series of curriculum material published by Digital for use with EduSystems and RSTS are listed below. Please inquire directly for prices on classroom quantities.

These publications may be ordered (cash enclosed) from:

Software Distribution Center
Digital Equipment Corporation
Maynard, Massachusetts 01754

| | | |
|---|---|---|
| Populution: Self Teaching BASIC Workbook | | $2.00 |
| 101 BASIC Computer Games | | $5.00 |
| Understanding Mathematics and Logic Using BASIC Computer Games | | $1.50 |
| | | |
| BASIC Matrix Operations, Project Solo | | $1.00 |
| Computer Augmented Calculus Topics | | $1.50 |
| Problems for Computer Mathematics | | $1.25 |
| Advanced Problems for Computer Mathematics | | $2.00 |
| Tutorial Exercises for Chemistry | Student Workbook | $1.00 |
| | Teacher's Resource | $2.75 |
| | | |
| BASIC Application Programs | | |
| Mathematics I | | $1.00 |
| Mathematics II | | 1.00 |
| Science | | 1.00 |
| Business and Social Studies | | 1.00 |
| Plotting | | 1.00 |
| Chemistry | | 1.50 |
| | | |
| Huntington I Application Programs | | |
| Mathematics | | $2.00 |
| Teacher Assistance | | 1.00 |
| | | |
| Huntington I Simulation Programs | | |
| Biology | | $1.00 |
| Chemistry | | 2.00 |
| Earth Science | | 1.00 |
| Physics | | 2.00 |
| Social Studies | | 1.00 |
| | | |
| Huntington II Simulation Modules | | |
| Student Workbook | | $.30 - .50 |
| Teacher's Guide | | .30 - .50 |
| Resource Handbook | | .50 - 1.00 |
| Program Paper Tape | | .50 - 1.00 |

# SCATER



# Teacher's Manual

A computer simulation of the use of alpha particle scattering to determine atomic structure

HUNTINGTON TWO COMPUTER PROJECT

Copyright © 1972, State University of New York

15 August 1973

The work of the Huntington Two Computer Project is partially
supported by the National Science Foundation, Grant GW-5883.
PUBLISHED EXCLUSIVELY BY DIGITAL EQUIPMENT CORPORATION, 1973

# *SCATER*

## TEACHER MANUAL

### Table of Contents

I. Basic Information about the Unit . . . . . . . . . . 1

II. Program Description . . . . . . . . . . . . . . . . 2

III. Sample Runs (*SCATR1*, *SCATR2*, *SCATR3*) . . . . . . . . 3

IV. Using the Programs in the Classroom . . . . . . . . 8

V. Follow-Up Questions . . . . . . . . . . . . . . . .12

# *SCATER*

## TEACHER MANUAL

## I. BASIC INFORMATION ABOUT THE UNIT

Subject Area: Physics

Topic: Atomic Theory -- Rutherford Scattering

Grade Level: 11 - 12

Computer Language: BASIC

Abstract:

*SCATER* simulates alpha particle scattering as demonstrated in the laboratory and according to three theoretical models of the atom: the hard sphere, the Thomson, and the Rutherford or nuclear model. *SCATR1* calculates the angular distribution of scattered alpha particles for an actual laboratory experiment. *SCATR2* plots angular distribution graphs for scattering according to each of the three models. *SCATR3* plots the trajectories of alpha particles scattered by target atoms of the Rutherford model.

The primary objectives of *SCATER* are: (1) to provide empirical evidence for the validity of the nuclear model of the atom, and (2) to permit students to study the mechanics of scattering on the level of individual atoms.

## II. PROGRAM DESCRIPTION

Since it is generally not possible to perform scattering experiments in a high school laboratory, *SCATER* was developed to assist students in understanding how scattering experiments are used to probe the atom and how the information obtained helps to explain atomic structure.

Students using these programs will gain insight into the actual experimental process as well as a first-hand experience with basic differences between the atoms of the hard-sphere, Thomson, and Rutherford models.

The scattering package includes three separate programs: *SCATR1*, *SCATR2* and *SCATR3*. *SCATR1* contains a simulation of Rutherford's experiment using a thin gold foil and the 5 MeV alpha particles emitted by radioactive polonium. This program permits students to gather information concerning the scattering of alpha particles from the gold foil. *SCATR2* produces theoretical angular distribution graphs for three atomic models to allow students to compare "actual" and theoretical results. The theoretical models include the hard-sphere model of kinetic theory, the plum-pudding model of J. J. Thomson, and Rutherford's nuclear model.

*SCATR3* calculates and plots trajectories for alpha particles scattered from individual Rutherford-type atoms. This program has been included to demonstrate the scattering mechanics so that students may see how the angular distribution graphs of *SCATR2* were produced.

A sample run of the three programs is included in Section II of this Manual. The STUDENT MANUAL contains instructions for using the programs.

# III. SAMPLE RUNS (*SCATR1, SCATR2, SCATR3*)

SCATR1

```
INSTRUCTIONS (0=NO,1=YES)? 1
A VERY RADIOACTIVE POLONIUM SOURCE PRODUCES A BEAM OF
100,000 ALPHA PARTICLES PER SECOND, EACH HAVING AN ENERGY
OF 5.3 MEV. THE BEAM STRIKES A 1 MICROMETER THICK GOLD FOIL.
FIVE ALPHA PARTICLE DETECTORS CAN BE SET UP TO COUNT THE
NUMBER OF SCATTERED PARTICLES DURING A COUNTING PERIOD OF
100,000 SECONDS (ABOUT 28 HOURS). EACH DETECTOR HAS AN AREA
OF 1 SQ CM AND IS 10 CM AWAY FROM THE GOLD FOIL.
THE ANGULAR LOCATION OF EACH OF THE COUNTERS CAN BE SET
BETWEEN THE LIMITS OF 10 DEGREES AND 180 DEGREES BY TYPING
A NUMBER BETWEEN 10 AND 180 WHEN THE COMPUTER ASKS: C()=.
ZERO DEGREES IS FORWARD SCATTERING AND 180 DEGREES IS
BACKWARD SCATTERING. TYPE C()=4 TO END THE PROGRAM.
C( 1 )=? 10
C( 2 )=? 30
C( 3 )=? 50
C( 4 )=? 70
C( 5 )=? 90
            ANGLE   NUMBER SCATTERED     FRACTION SCATTERED
             10      1.161718E+6          1.160000E-4
             30      14897                1.490000E-6
             50      2185                 2.180000E-7
             70      662                  6.620000E-8
             90      258                  2.580000E-8
C( 1 )=? 100
C( 2 )=? 120
C( 3 )=? 140
C( 4 )=? 160
C( 5 )=? 180
             100     191                  1.910000E-8
             120     123                  1.230000E-8
             140     104                  1.044000E-8
             160     86                   8.610000E-9
             180     70                   7.010000E-9
C( 1 )=? 4
```

SCATR2

```
INSTRUCTIONS (0=NO,1=YES)? 1
SCATR2 PLOTS THEORETICAL PREDICTIONS OF THE FRACTION OF
ALPHA PARTICLES SCATTERED AT ANGLES FROM 10 TO 180
DEGREES BY THREE DIFFERENT HEAVY ATOM MODELS.
INPUTS ARE: ALPHA PARTICLE ENERGY (BETWEEN 2 AND 8 MEV),
TARGET MATERIAL (1=COPPER,2=SILVER,3=GOLD),TARGET THICKNESS
(BETWEEN .5 AND 2 MICROMETERS), DETECTOR SIZE
(BETWEEN .5 AND 2 CM↑2), AND DISTANCE FROM TARGET TO
DETECTORS (BETWEEN 10 AND 40 CM).

ENERGY= 5.3 ? 5.3
MATERIAL= 3 ? 3
THICKNESS= 1 ? 1
SIZE= 1 ? 1
DISTANCE= 10 ? 10
MODEL (1=HARD SPHERES, 2=THOMSON, 3=RUTHERFORD)? 1

HARD SPHERE MODEL
 5.3 MEV ALPHA'S   1 MICRON GOLD   1 SQ CM COUNTERS  10 CM AWAY

               FRACTION OF PARTICLES SCATTERED (LOG SCALE)
       1E-9      1E-8      1E-7      1E-6      1E-5      1E-4      1E-3
ANGLE: I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I
 10    I                               *
 20    I                               *
 30    I                               *
 40    I                               *
 50    I                               *
 60    I                               *
 70    I                               *
 80    I                               *
 90    I                               *
 100   I                               *
 110   I                               *
 120   I                               *
 130   I                               *
 140   I                               *
 150   I                               *
 160   I                               *
 170   I                               *
 180   I                               *
       I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I

NEXT PREDICTION (1=NEW MODEL, 2=NEW ENERGY, ETC.,3=END PROGRAM? 1
MODEL (1=HARD SPHERES, 2=THOMSON, 3=RUTHERFORD)? 2
```

**SCATR2 (cont.)**

```
THOMSON MODEL
 5.3 MEV ALPHA'S   1 MICRON GOLD   1 SQ CM COUNTERS   10 CM AWAY

               FRACTION OF PARTICLES SCATTERED (LOG SCALE)
       1E-9      1E-8      1E-7      1E-6      1E-5      1E-4      1E-3
ANGLE: I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I
 10    *
 20    *
 30    *
 40    *
 50    *
 60    *
 70    *
 80    *
 90    *
 100   *
 110   *
 120   *
 130   *
 140   *
 150   *
 160   *
 170   *
 180   *
       I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I

NEXT PREDICTION (1=NEW MODEL, 2=NEW ENERGY, ETC.,3=END PROGRAM? 1
MODEL (1=HARD SPHERES, 2=THOMSON, 3=RUTHERFORD)? 3

RUTHERFORD MODEL
 5.3 MEV ALPHA'S   1 MICRON GOLD   1 SQ CM COUNTERS   10 CM AWAY

               FRACTION OF PARTICLES SCATTERED (LOG SCALE)
       1E-9      1E-8      1E-7      1E-6      1E-5      1E-4      1E-3
ANGLE: I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I
 10    I                                                  *
 20    I                                      *
 30    I                               *
 40    I                          *
 50    I                       *
 60    I                    *
 70    I                 *
 80    I               *
 90    I              *
 100   I            *
 110   I           *
 120   I          *
 130   I         *
 140   I         *
 150   I        *
 160   I        *
 170   I        *
 180   I        *
       I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I  .  . ..I

NEXT PREDICTION (1=NEW MODEL, 2=NEW ENERGY, ETC.,3=END PROGRAM? 3
INSTRUCTIONS (0=NO,1=YES)? 1
SCATR3 PLOTS THE TRAJECTORIES OF ALPHA
PARTICLES SCATTERED FROM INDIVIDUAL HEAVY ATOMS.
INPUTS ARE: ALPHA PARTICLE ENERGY (BETWEEN 2 AND 8 MEV),
TARGET MATERIAL (1=COPPER,2=SILVER,3=GOLD),
AND THREE DIFFERENT PERPENDICULAR DISTANCES BETWEEN THE
INCIDENT ALPHA PATH AND THE CENTER OF THE TARGET ATOM.
ALPHA ENERGY= 5.3 ? 5.3
TARGET MATERIAL= 3 ? 3
CHOOSE X() BETWEEN-200000 AND 200000 (FEMTOMETERS)
X( 1 )=-160000 ? -160000
X( 2 )=-40000 ? -40000
X( 3 )= 80000 ? 80000


             ALPHA ENERGY: 5.3 MEV        TARGET CHARGE: 79

          X(1)=-160000       X(2)=-40000         X(3)= 80000

                              (FEMTOMETERS)
        X=     -200000   -100000    0         100000    200000
Y=         -----I---------I---------I---------I---------I-----
-224000   I         1           2           3

-192000   I         1         B 2         B 3

-160000   I         1   B       2           3  B

-128000   I         1B          2           3     B

-96000    I       B 1           2           3        B

-64000    I      B  1           2           3         B

-32000    I     B   1           2           3          B

 0        I     B   1           2   N       3          B

 32000    I     B   1           2           3          B

 64000    I      B  1           2           3         B

 96000    I       B 1           2           3        B

 128000   I         1B          2           3     B

 160000   I         1   B       2           3  B

 192000   I         1         B 2         B 3

 224000   I         1           2           3
           -----I---------I---------I---------I---------I-----
ANGLE( 1 )= .01       ANGLE( 2 )= .06         ANGLE( 3 )= .03

1=NEW DISTANCES, 2=NEW ENERGY OR TARGET, 3=END PROGRAM? 1
```

SCATR3 (cont.)

```
X( 1 )=-160000 ? -160
X( 2 )=-40000 ? 40
X( 3 )= 80000 ? -5

              ALPHA ENERGY: 5.3 MEV            TARGET CHARGE: 79

           X(1)=-160             X(2)= 40              X(3)=-5

                                  (FEMTOMETERS)
         X=     -200000    -100000      0         100000     200000
Y=           -----I----------I----------I----------I----------I-----
-224000    I                3           2

-192000    I                 3   B      2     B

-160000    I               B   3        2            B

-128000    I            B        3      2               B

-96000     I        B              3    2                   B

-64000     I       B                 3  2                    B

-32000     I      B                   3 2                     B

  0        I      B                     N                     B

 32000     I      B                    1      2               B

 64000     I       B                  1            2         B

 96000     I        B                1                  2   B

 128000    I            B            1                   B   2

 160000    I               B        1                 B             2

 192000    I                      B1           B

 224000    I                      1
             -----I----------I----------I----------I----------I-----
ANGLE( 1 )= 15.18        ANGLE( 2 )= 56.13        ANGLE( 3 )= 153.61

1=NEW DISTANCES, 2=NEW ENERGY OR TARGET, 3=END PROGRAM? 3
```

## IV. USING THE PROGRAMS IN THE CLASSROOM

The *STUDENT MANUAL* was designed to be as self-sufficient as possible; however, it is suggested that the teacher review the following before using the scattering programs:

1) A brief history of the development of atomic theory, including a description of the hard-sphere, Thomson, and Rutherford models.

2) How the discovery of radioactive materials made it possible to probe the microscopic world of the atom; that is, what is alpha particle scattering? How is the information about the atom obtained?

3) A description of the experiment simulated in the program, including some discussion of the concept of the angular distribution of scattered alpha particles (see *STUDENT MANUAL*).

The scattering programs may be used with either large or small groups; in addition, simple modifications of the basic program will allow independent study for the more highly motivated student. Each mode of presentation is outlined below.

### A. Large Group Instruction (Conventional Classroom)

1) Presentation of a blackboard diagram of the experimental set-up and a verbal description of the experiment. Discussion of the three theoretical models of atomic structure. (See figures and descriptions in the *RESOURCE MANUAL* and the *STUDENT MANUAL*.) One or more students may be assigned to the computer terminal to type in information and read out the results.

2) Selection of various counter locations *(SCATR1)*. The fraction of particles collected by each counter is plotted on the blackboard, with the fraction plotted along the ordinate (a log scale may be convenient), and the counter locations (in degrees) plotted along the abscissa. Further selection of locations will produce a complete and smooth curve.

3) Obtain the angular distribution graphs by running *SCATR2*. (These graphs can be obtained before class and reproduced on dittos for class distribution.) By comparing the theoretical curves with the experimental curve, a student can readily identify the Rutherford model as the most accurate atomic model.

4) To show how the angular distribution curves were obtained, run *SCATR3* several times and assign students to reproduce the trajectories obtained on the blackboard. Be sure to have the deflected path lines extended.

The angular distribution is really a probability distribution. The angular distribution is obtained from the trajectories by assuming that alpha particles move toward the target atom with random perpendicular distances between their undeflected paths and the center of the target atom. All alphas coming in at the same perpendicular distance are scattered through the same angle θ. Once the probability of an incoming alpha having the perpendicular distance X is known (the probability turns out to be proportional to X), the probability of scattering into the angle θ can be found. This requires some mathematics, but even without math some of the features of the trajectory plots can be related to features of the associated angular distribution.

5) The following observations about the behavior of each model could be made at this point in the presentation:

a) Hard-Sphere Model. For frictionless collisions between hard spheres the angle of reflection is equal to the angle of incidence. For curved surfaces, the angles are measured with respect to the normal to the surface; that is, the radius of the sphere extended through the point of impact. (Notice that the *scattering* angle is $180^\circ$ minus the sum of the incident and reflected angles.) The scattering is not dependent on the charge of the particles. Since typical scattering foils are about a thousand atoms thick and still do not scatter all of the incident alpha particles, this model is in contradiction with experiment.

If the hard-sphere model is fixed up by assuming that the target atoms are *transparent* hard spheres and that most of the incident alpha particles go right through the target atoms, the angular distribution plotted in *SCATR2* is obtained. This is equivalent to assuming that the radius of the hard-sphere target atoms is small compared with their center-to-center spacing.

b) Thomson Model. No interaction occurs until the particle actually enters the atom, since the resultant force outside the atom is zero. As the alpha particle approaches the center of the atom, the electric deflecting force inside the atom is reduced because the particle "sees" only the positive charge in the sphere between it and the center of the atom.

c) Rutherford Model. No interaction occurs outside the atom since, again, the resultant force outside the atom is zero. Once the alpha particle is inside the atom, it is influenced primarily by the positive nuclear charge (the electrons are assumed to have little or no effect on the alpha particle, due to their small mass) and experiences very strong forces close to the nucleus.

B. Small Groups (possibly during lab periods)

1) Let several small groups run the programs as outlined in the *STUDENT MANUAL*.

2) If several groups are involved simultaneously, each group may be given one of the models and assigned to investigate the scattering process for that model.

3) Following completion of (2), let the groups present their findings to the remainder of the class, trying to answer any questions that may arise.

C. Independent Study (or extended study)

In addition to the approaches outlined above, *SCATR2* permits students to vary such parameters as the charge of the target atom, the incident alpha particle energy, and the foil thickness. Individuals or independent study groups may thereby determine:

1) how varying the alpha particle energy affects the angular distribution of scattered particles;

2) the effect of different nuclear charges on the angular distribution; and

3) how the foil thickness affects the scattering of alpha particles.

It might be best to limit these investigations to the (correct) Rutherford model of the atom.

Students who want to examine the trajectories in *SCATR3* in more detail can change the magnification of the scattering picture by deleting one program line as indicated by a REM statement in the program. By increasing the magnification, the actual trajectory shape (instead of just the angle at which the particle is scattered) can be determined for particles with small (5 to 100 femtometers) impact parameters. The magnification is initially set at the low value of $2.5 \times 10^8$ in order to show just how few of the alpha particles going through the atom are appreciably scattered. Higher magnification will allow more detail to be seen in trajectories that pass close to the nucleus.

## V. FOLLOW-UP QUESTIONS

1. *HOW WOULD YOU DESCRIBE THE TYPE OF SCATTERING PRODUCED BY EACH MODEL? FOR WHICH ATOMIC MODEL IS THE ANGULAR DISTRIBUTION OF ALPHA PARTICLES MOST LIKE WHAT YOU OBSERVED FOR THE EXPERIMENT?*

   a) Hard-Sphere Model -- the particles are scattered equally in all directions, i.e., the fraction of particles scattered is the same for every angle.

   b) Thomson Model -- very little scattering; most particles scattered near 0°.

   c) Rutherford Model -- most of the particles are scattered through small angles with a small number scattered through very large ($>90^{o}$) angles.

   The Rutherford Model best describes the structure of the atom.

2. *A MECHANICAL ANALOG CAN BE CONSTRUCTED TO DEMONSTRATE THE DEFLECTION OF ALPHA PARTICLES IN A COULOMB FORCE FIELD. A STEEL BALL ROLLED TOWARD A HILL WILL TRACE A PATH LIKE THAT TAKEN BY AN ALPHA PARTICLE AS IT APPROACHES THE NUCLEUS. IN THE CASE OF THIS MECHANICAL MODEL, GRAVITATIONAL POTENTIAL REPLACES THE ELECTRIC POTENTIAL OF THE COULOMB FORCE FIELD. TO MAKE THIS MODEL MORE REALISTIC, HOW MUST THE "HILL" BE CONSTRUCTED?*

   Since the Coulomb potential varies as $1/r$, the height of the hill must be inversely proportional to the distance from the center of the hill.

3. *IN QUESTION #2, HOW WOULD YOU DIFFERENTIATE BETWEEN A "HILL" FOR THE COPPER NUCLEUS AND ONE FOR A GOLD NUCLEUS?*

   Since copper has a lesser charge, the "hill" representing the copper nucleus would not be as high as that representing the gold nucleus.

* 4. *A STEEL BALL WITH KINETIC ENERGY E HEADING DIRECTLY FOR THE CENTER OF THE HILL CAN ONLY CLIMB UP THE POTENTIAL HILL UNTIL ITS KINETIC ENERGY IS REDUCED TO ZERO AND ALL OF ITS ENERGY IS POTENTIAL ENERGY. IT THEN ROLLS BACK DOWN THE HILL AND REGAINS ALL OF ITS ORIGINAL KINETIC ENERGY. AT THE POINT AT WHICH IT IS HIGHEST ON THE HILL AND ITS KINETIC ENERGY IS ZERO, IT IS AS CLOSE AS IT WILL EVER GET TO THE CENTER OF THE ATOM. CALL THIS DISTANCE OF CLOSEST APPROACH D. HOW WOULD YOU CALCULATE THE DISTANCE OF CLOSEST APPROACH, D, FOR ALPHA PARTICLES SCATTERED FROM ATOMS?*

By equating the original kinetic energy E to the Coulomb potential at the distance D, and solving for D:

$$E = \left[k\ Q\ q\right] \frac{1}{D}$$

$$D = \left[k\ Q\ q\right] \frac{1}{E} = \left[Ze\ 2e\right] \frac{1}{E} = \frac{2Ze^2}{E} = \frac{2Zr_e m_e c^2}{E}$$

Where Z is the atomic number of the target atom, e is the charge of an electron, and 2e is the charge of the alpha particle.

The problem of units was avoided here again by replacing $e^2$ by

$$e^2 = r_e m_e c^2 \ ;$$

$r_e$ is the "classical electron radius":

$$r_e = 2.8 \times 10^{-15} \text{ meters}$$

and $m_e c^2$ is the rest energy of an electron:

$$m_e c^2 = .511 \text{ MeV}$$

* 5. *WHEN AN ALPHA PARTICLE GETS WITHIN ABOUT* $8.8 \times 10^{-15}$ *METERS OF THE CENTER OF A GOLD ATOM, IT BEGINS TO FEEL A STRONG FORCE DUE TO THE NUCLEUS IN ADDITION TO THE ELECTRIC REPULSION. THIS STRONG OR NUCLEAR FORCE IS NOT COMPLETELY UNDERSTOOD AND IS STILL BEING STUDIED BY NUCLEAR AND ELEMENTARY PARTICLE PHYSICISTS. WHAT ORIGINAL KINETIC ENERGY MUST AN ALPHA PARTICLE HAVE IN ORDER TO GET CLOSE ENOUGH TO THE NUCLEUS OF A GOLD ATOM TO FEEL THE STRONG NUCLEAR FORCE?*

Set D in the above expressions equal to $8.8 \times 10^{-15}$m and solve for E:

$$E = 2Z \frac{m_e c^2}{D} 2.8 \times 10^{-15} = \frac{2 \times 79 \times .511 \times 2.8 \times 10^{-15}}{8.8 \times 10^{-15}} = 25 \text{ MeV}$$

No radioactive source produces alpha particles with energies as high as 25 MeV, but machines can accelerate particles to that energy. The National Accelerator Laboratory machine in Batavia, Illinois, can accelerate protons to over 300,000 MeV, allowing exploration deep inside the nucleus of atoms.

* 6. *ALTHOUGH RUTHERFORD'S MODEL BEST EXPLAINED THE RESULTS OF THE SCATTERING EXPERIMENTS, IT IS CLAIMED THAT HIS MODEL CANNOT BE A COMPLETE DESCRIPTION OF THE ATOM. WHY?*

To move in curved paths, objects must be accelerated. When electric charges are accelerated, they radiate energy in the form of light. Thus, the orbiting electrons of the Rutherford Model would radiate away their energy and eventually spiral into the nucleus.

---

* Indicates questions of greater difficulty.